Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Coding Metamaterials, Digital Metamaterials and Programmable Metamaterials

by:
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Abstract: As artificial structures, metamaterials are usually described by macroscopic effective medium parameters, which are named as “analog metamaterials”. Here, we propose “digital metamaterials” in two steps. Firstly, we present “coding metamaterials” that are composed of only two kinds of unit cells with 0 and π phase responses, which we name as “0” and “1” elements. By coding “0” and “1” elements with controlled sequences (i.e., 1-bit coding), we can manipulate electromagnetic (EM) waves and realize different functionalities. The concept of coding metamaterial can be extended from 1-bit coding to 2-bit or more. In 2-bit coding, four kinds of unit cells with phase responses 0, π/2, π, and 3π/2 are required to mimic “00”, “01”, “10” and “11” elements, which have larger freedom to control EM waves. Secondly, we propose a unique metamaterial particle which has either “0” or “1” response controlled by a biased diode. Based on the particle, we present “digital metamaterials” with unit cells having either “0” or “1” state. Using the field-programmable gate array, we realize to control the digital metamaterial digitally. By programming different coding sequences, a single digital metamaterial has distinct abilities in manipulating EM waves, realizing the “programmable metamaterials”. The above concepts and physical phenomena are confirmed by numerical simulations and experiments through metasurfaces.

Keywords: Coding metamaterial, digital metamaterial, programmable metamaterial, real-time control of metamaterials

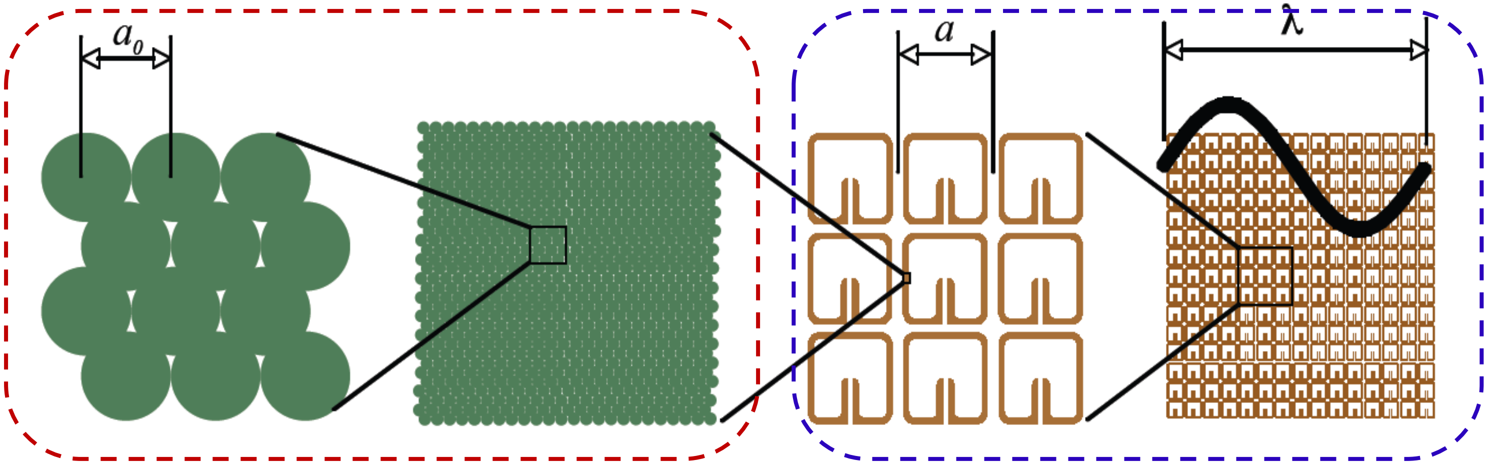
References

1. T. J. Cui, M. Q. Qi, X. Wan, J. Zhao, and Q. Cheng, “Coding metamaterials, digital metamaterials and programmable metamaterials,” Light: Science & Applications 3, e218; doi:10.1038/lsa.2014.99, 2014
2. L. H. Gao *et* al., “Broadband diffusions of terahertz waves by multi-bit coding metasurfaces,” submitted for publication, 2014

Outline

- Background and motivation
- Coding metamaterials
- Digitally controlled metamaterials
- Programmable metamaterials
- Conclusions

Background



Atoms **Medium** **Artificial Atom** **Effective Medium**

- Artificial atoms: Arbitrarily designed; Countless
- Arrangements: arbitrary

- Provide special medium parameters that cannot be realized in nature

Cooperated with the transformation optics, metamaterials can be used to control EM waves, bringing new physical phenomena.

Background: Effective Medium

Metamaterial: Described by Effective Medium Theory

$$\varepsilon_{\text{eff}} = \bar{\varepsilon}\frac{(\theta/2)}{\sin(\theta/2)}[\cos(\theta/2)]^{-S_b},$$

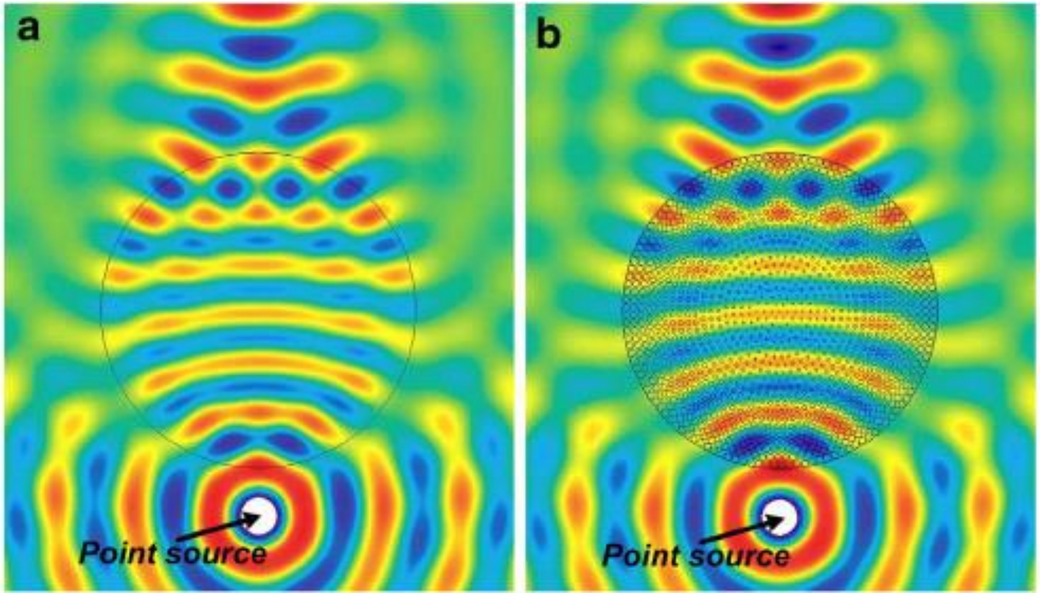
$$\mu_{\text{eff}} = \bar{\mu}\frac{(\theta/2)}{\sin(\theta/2)}[\cos(\theta/2)]^{S_b}.$$

Liu, Cui, et al., *PRE* 76, 026606 (2007)
Smith & Pendry, *JOSA-B* 23, 391 (2006)
Smith et al., *PRE* 71, 036617 (2005)

Left: Effective medium

Right: Real structure

Ma & Cui, Nat. Comm., June 2010

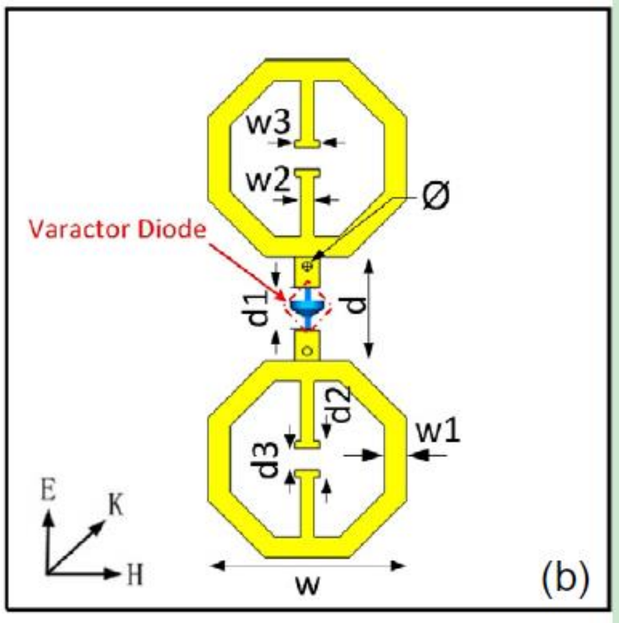


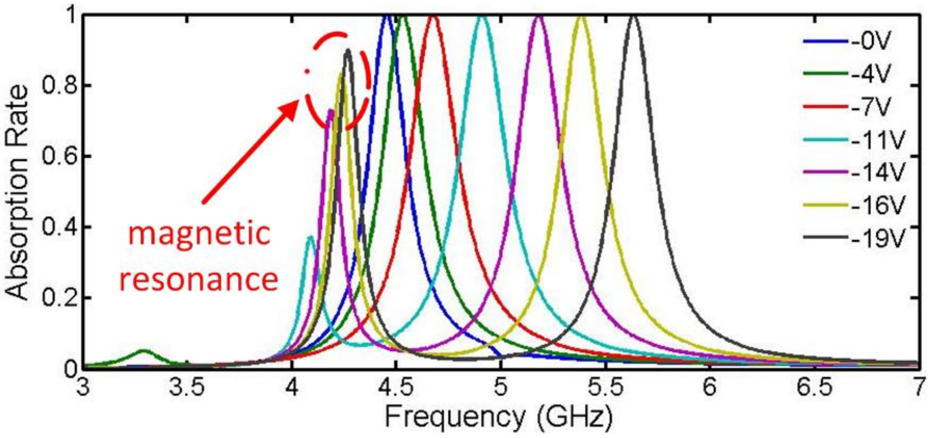
Metamaterials based on effective medium has been well developed.

Background: Problems

Big Advantage of Metamaterials: Controlling EM Waves

- ➢ **Design metamaterials (e.g. using transformation optics) to realize certain functionality (e.g. cloaks)**
- ➢ **Once fabricated, the function cannot be controlled**


w3
w2
Ø
Varactor Diode
d1
d
d2
d3
w1
E
K
H
w
(b)



Zhao et al., New J. Phys. **15,** 043049 (2013)

Tunable Metamaterials

- ➢ **Small tunable range**
- ➢ **Cannot be real-time control**

Background: Our Motivation

1. **Can we make instant or real-time controls of EM waves by metamaterials?**
2. **Can we realize significant tunable or even switchable functionalities of a single metamaterial?**

Background: A Lessen from Circuit

Circuits

- Analog Circuits: Continuous currents
- Digital Circuits: People use the coding of 0 and 1 to process information.

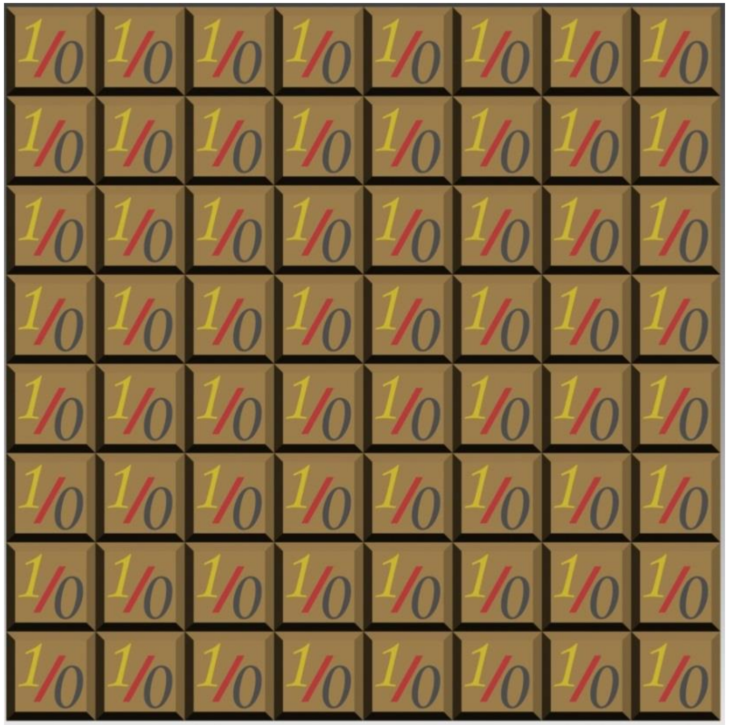
Metamaterials

- The current metamaterials are based on continuous medium parameters, which can be considered as analog metamaterials.

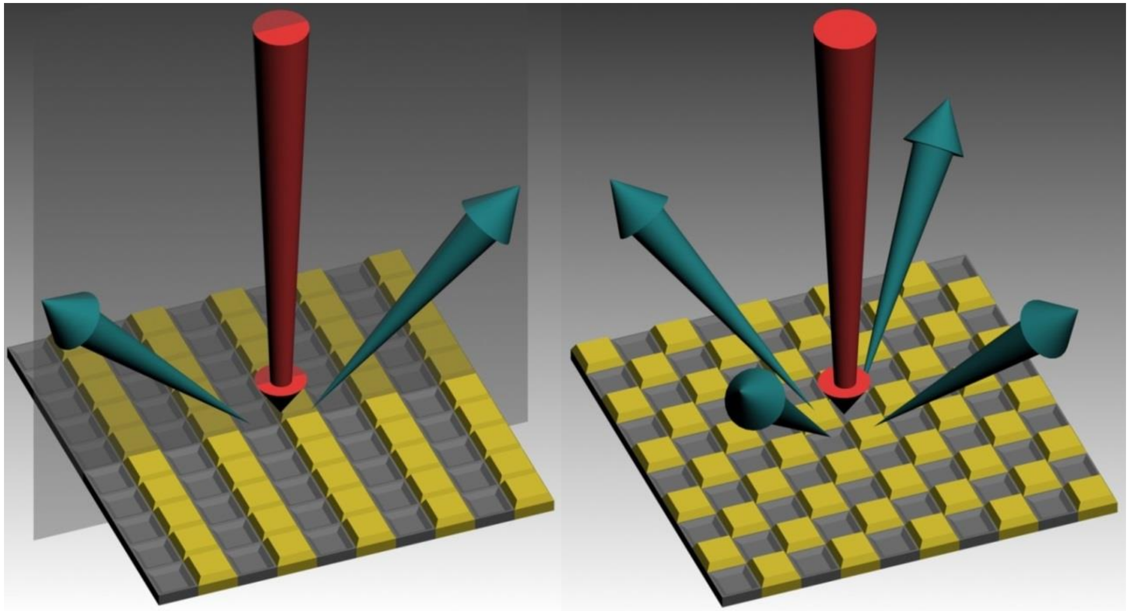
- We propose the concept of coding metamaterial, which can be further extended to programmable metamaterial.

Coding Metamaterials

1-Bit Coding Metamaterials


1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0
1/0 1/0 1/0 1/0 1/0 1/0 1/0 1/0

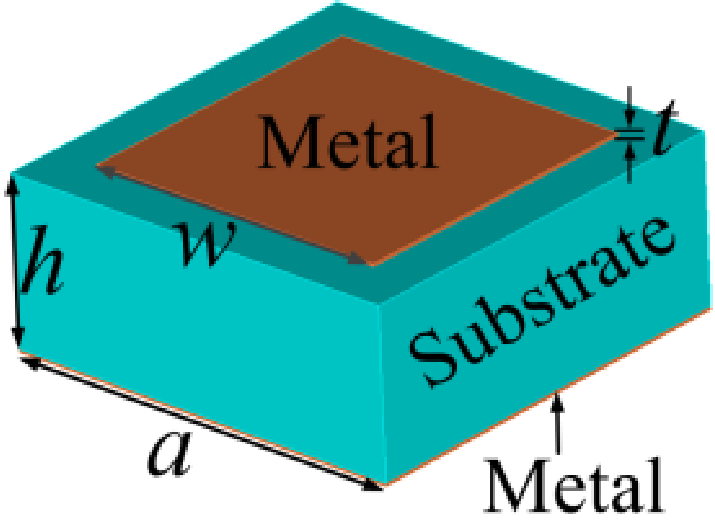
- **0 Unit: 0 Phase**
- **1 Unit: 180 Phase**



- **Control EM waves by changing the coding sequences of 0 and 1 units**

Cui et al., Light: Science & Applications 3, e218; doi:10.1038/lsa.2014.99, 2014

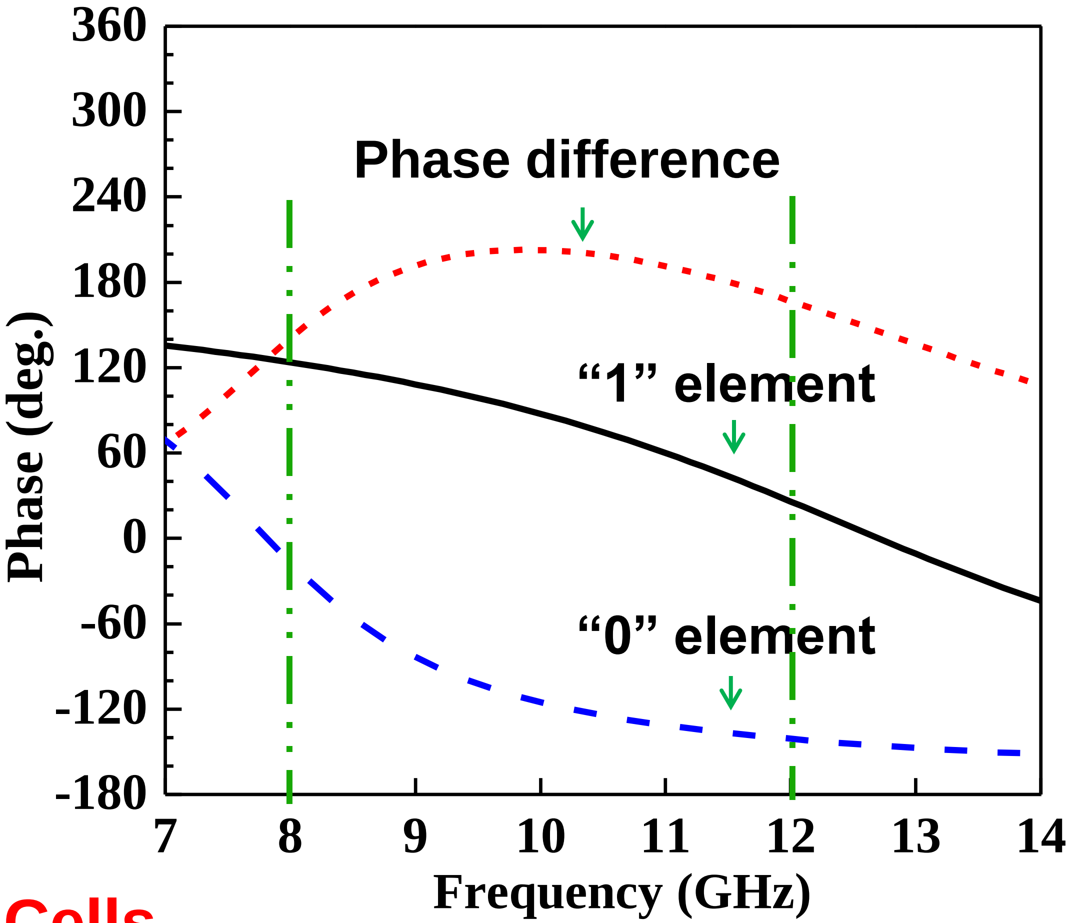
Coding Metamaterials


Metal
t
h
w
Substrate
a
Metal

Basic Element

a = 5 mm, *h* =1.964 mm,
t = 0.018 mm
w = 4.8 mm: 0 Unit
w = 3.75 mm: 1 Unit

Phase Responses



Realization of 0/1 Unit Cells

Coding Metamaterials

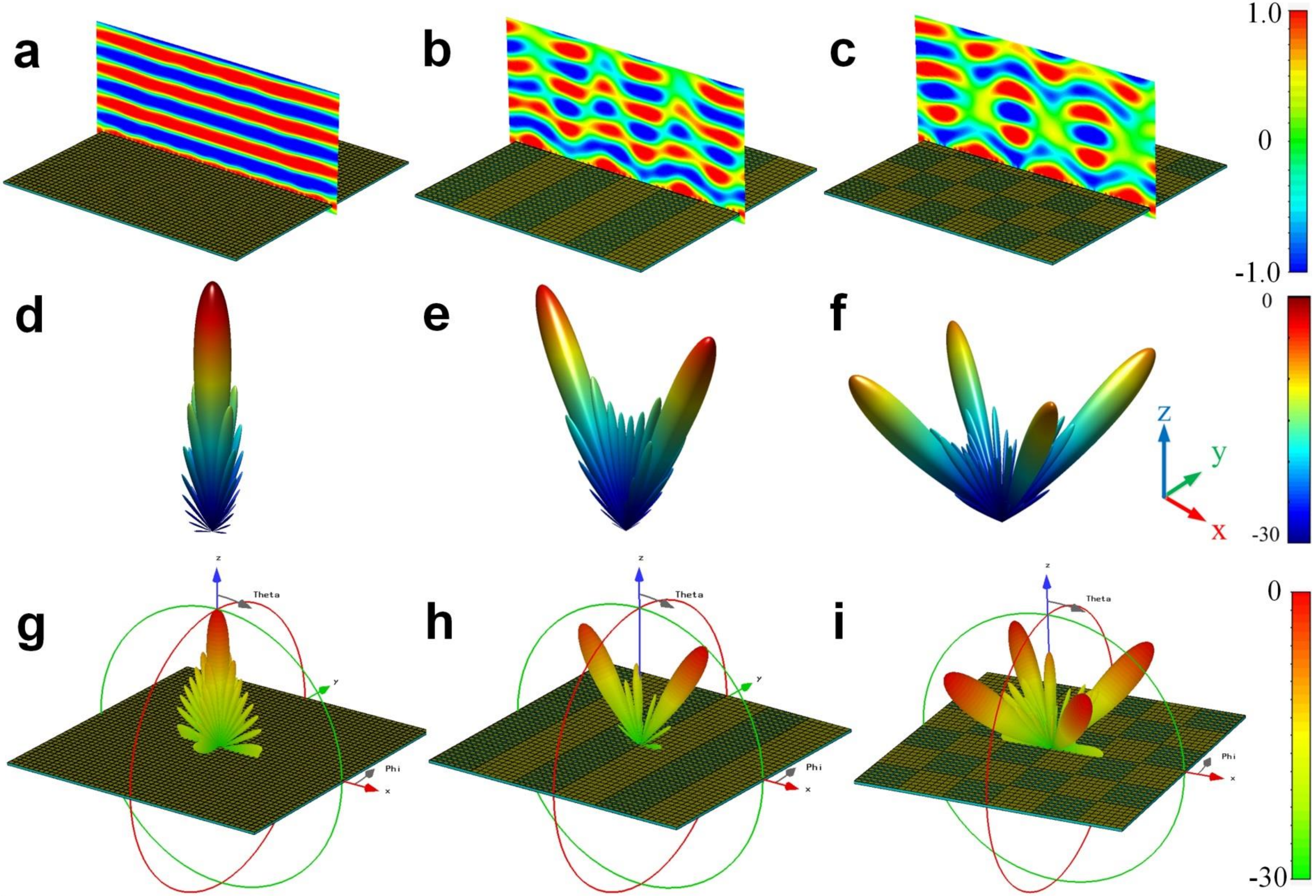
The radiation and scattering patterns can be controlled by coding the 0 and 1 elements:

$$f(\theta,\varphi) = f_e(\theta,\varphi)\sum_{m=1}^{N}\sum_{n=1}^{N}\exp\{-i\{\varphi(m,n) + kD\sin\theta[(m-1/2)\cos\varphi + (n-1/2)\sin\varphi]\}\},$$

$$\mathrm{Dir}(\theta,\varphi) = 4\pi\left|f(\theta,\varphi)\right|^2 / \int_0^{2\pi}\int_0^{\pi/2}\left|f(\theta,\varphi)\right|^2 \sin\theta d\theta d\varphi.$$

Solving the inverse problem, given arbitrary wave patterns, we can design the corresponding coding sequences of 0 and 1 elements.

1-Bit Coding Metamaterials


a
b
c
1.0
0
-1.0
d
e
f
0
-30
z
y
x
g
h
i
z
Theta
y
Phi
x
0
-30

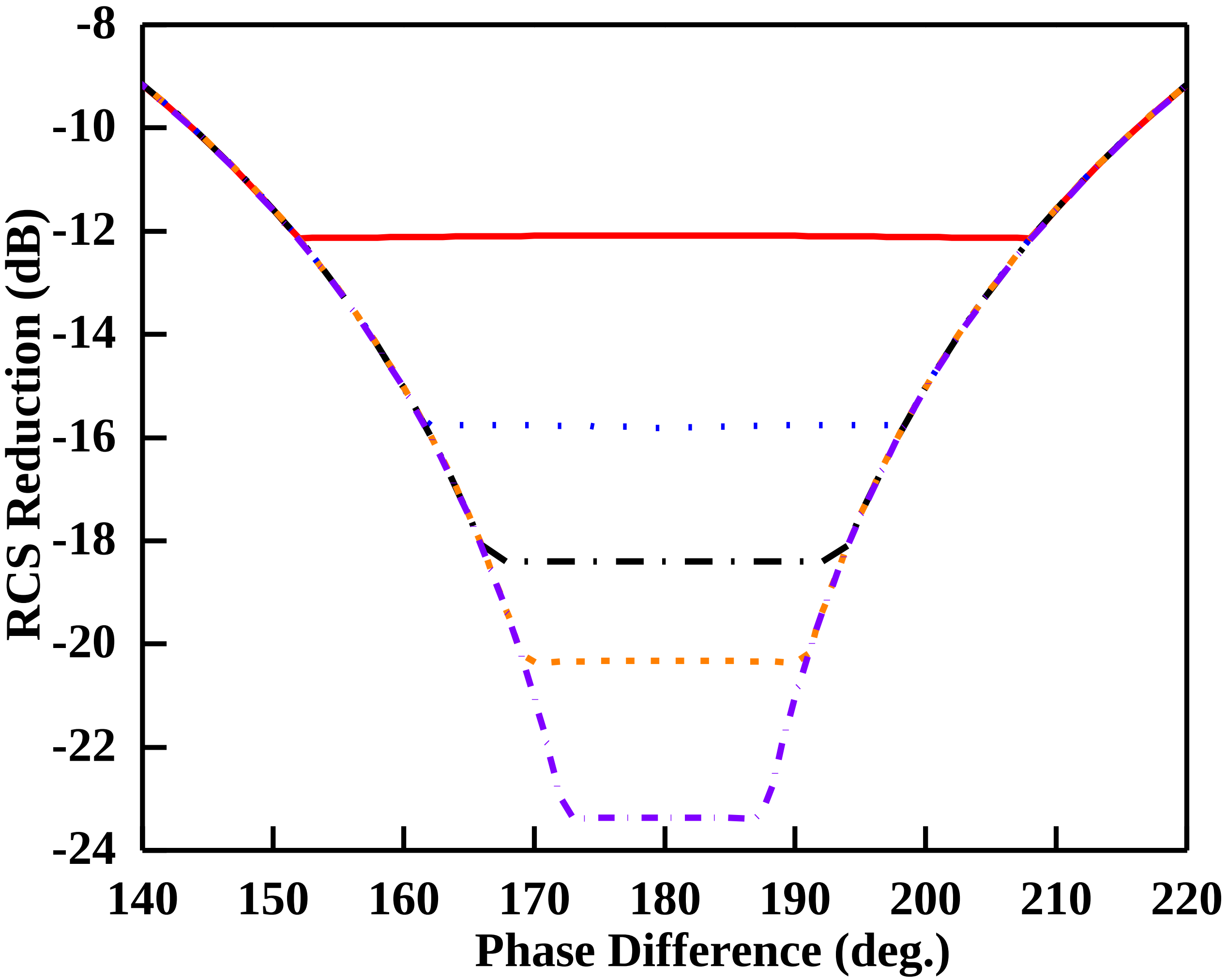
1-Bit Coding Metamaterials

The optimized codes for different lattice numbers *N*

Design Example:
RCS Reduction –
A New Strategy of
Cloaking

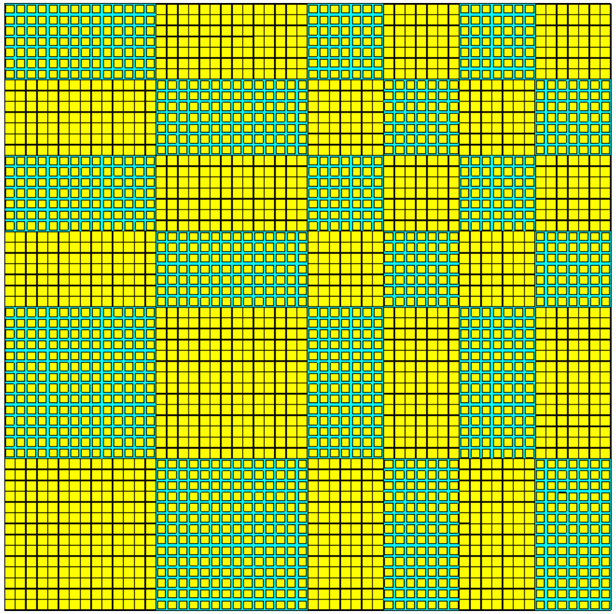
N	Code Sequence	RCS Reduction (dB)
6	001011	-12.08
7	0011010	-14.64
8	00110101	-15.82
10	0001010110	-18.39
12	001001110101	-19.75
14	00111110110101	-21.41
16	0011110110101010	-22.37
20	01000100110000110101	-23.58

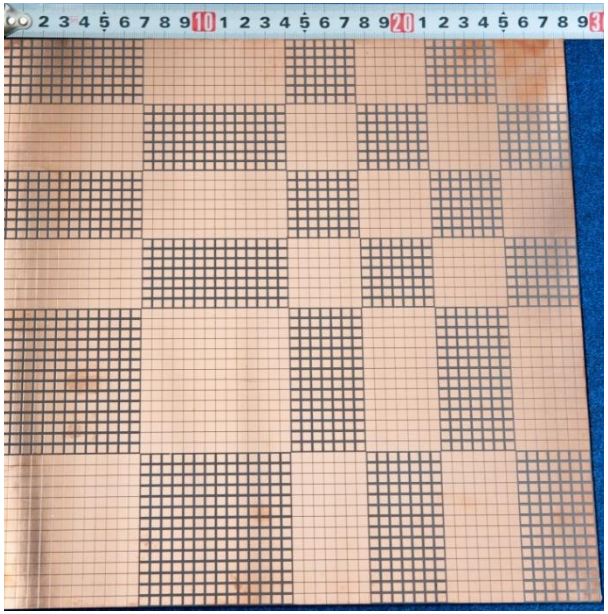
1-Bit Coding Metamaterials

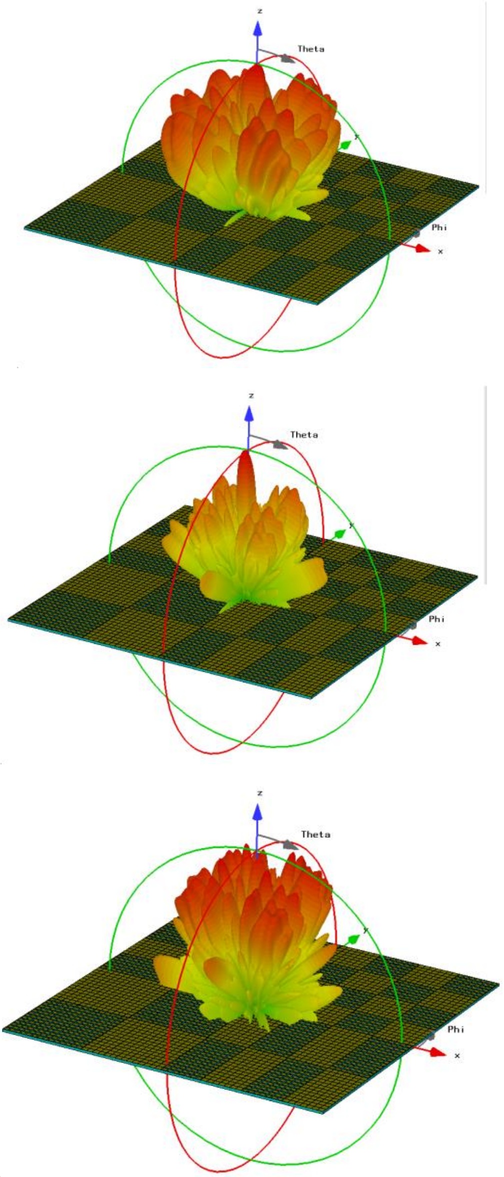


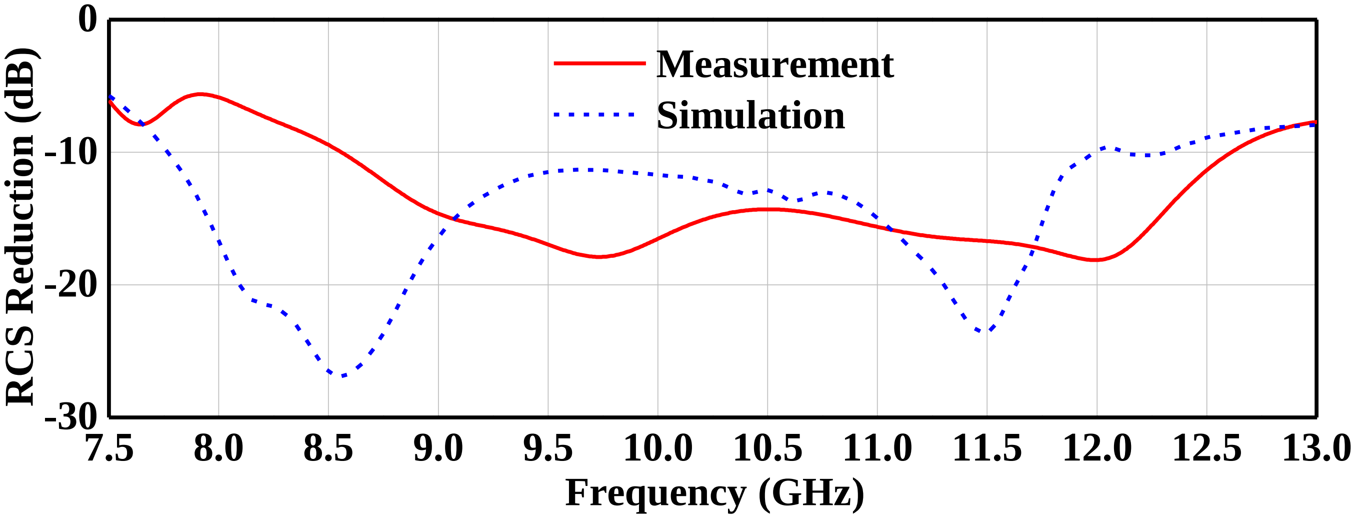
Good tolerance of RCS reduction to the phase difference, which results in wideband performance

1-Bit Coding Metamaterials



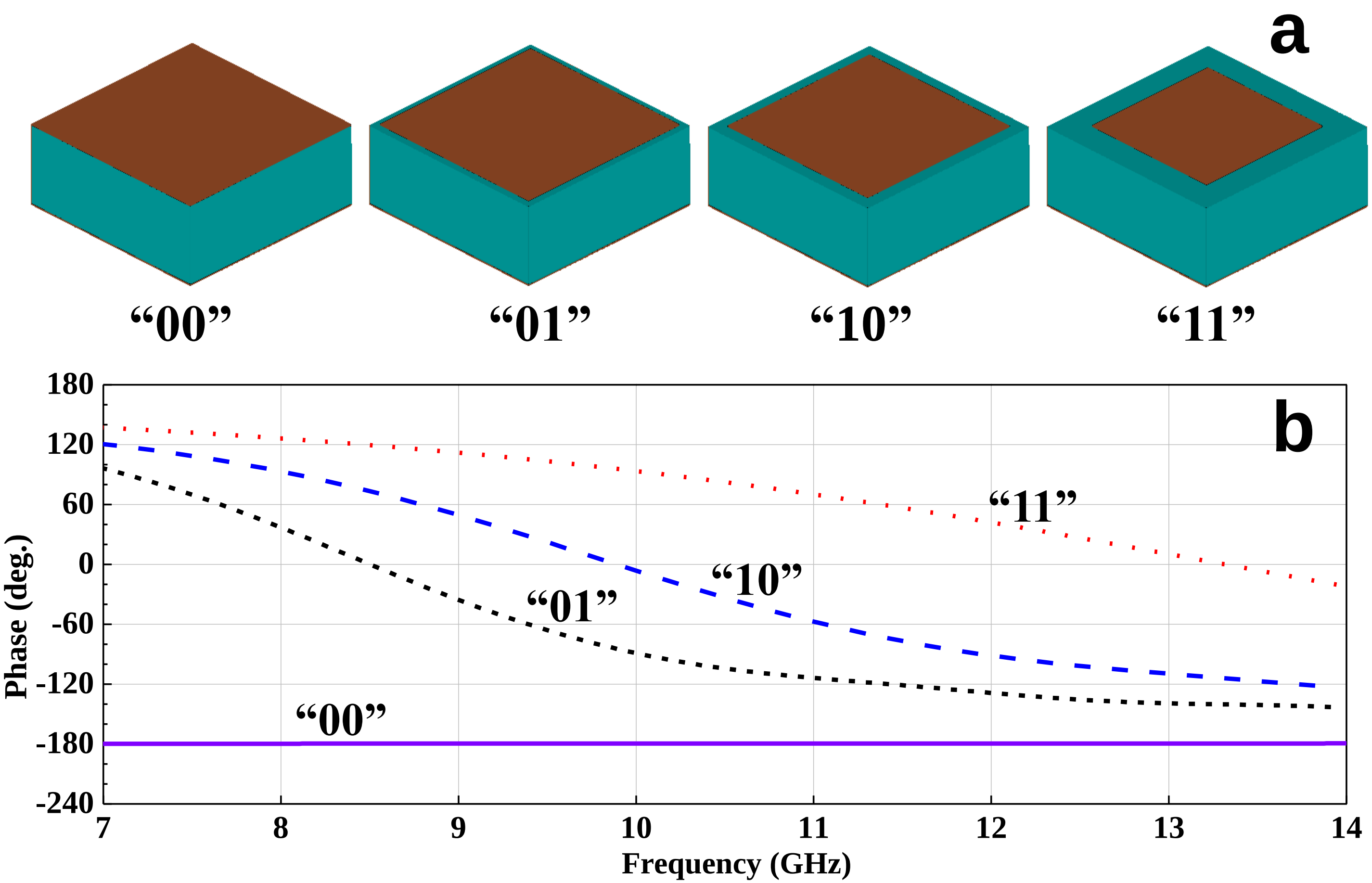



z
Theta
y
Phi
x
z
Theta
y
Phi
x
z
Theta
y
Phi
x



1-Bit Coding Metasurface for RCS Reduction

2-Bit Coding Metamaterials



2-Bit Coding Metamaterial - Four Basic Elements

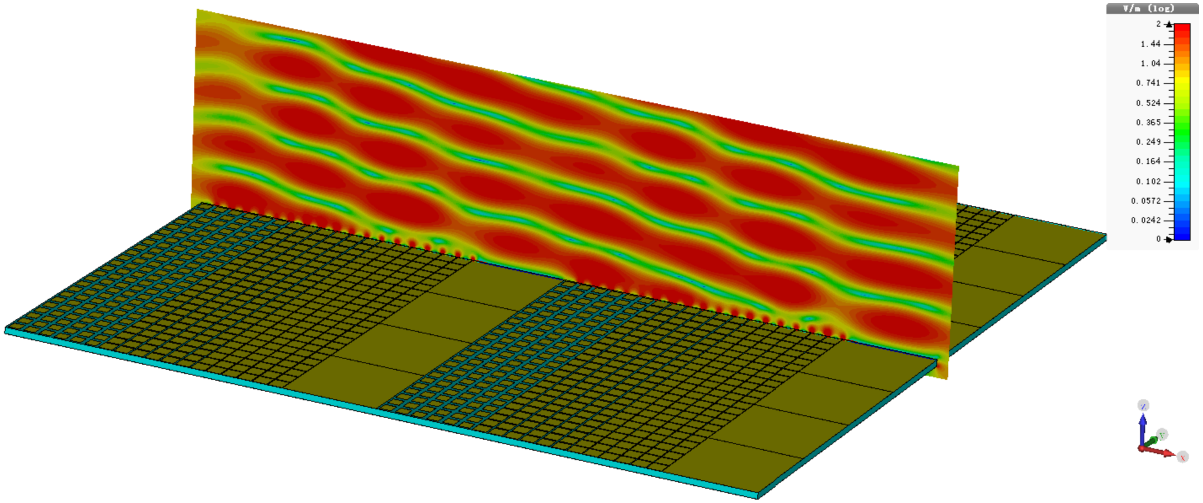
"00" – 0; "01" – 90; "10" – 180; "11" – 270

2-Bit Coding Metamaterials

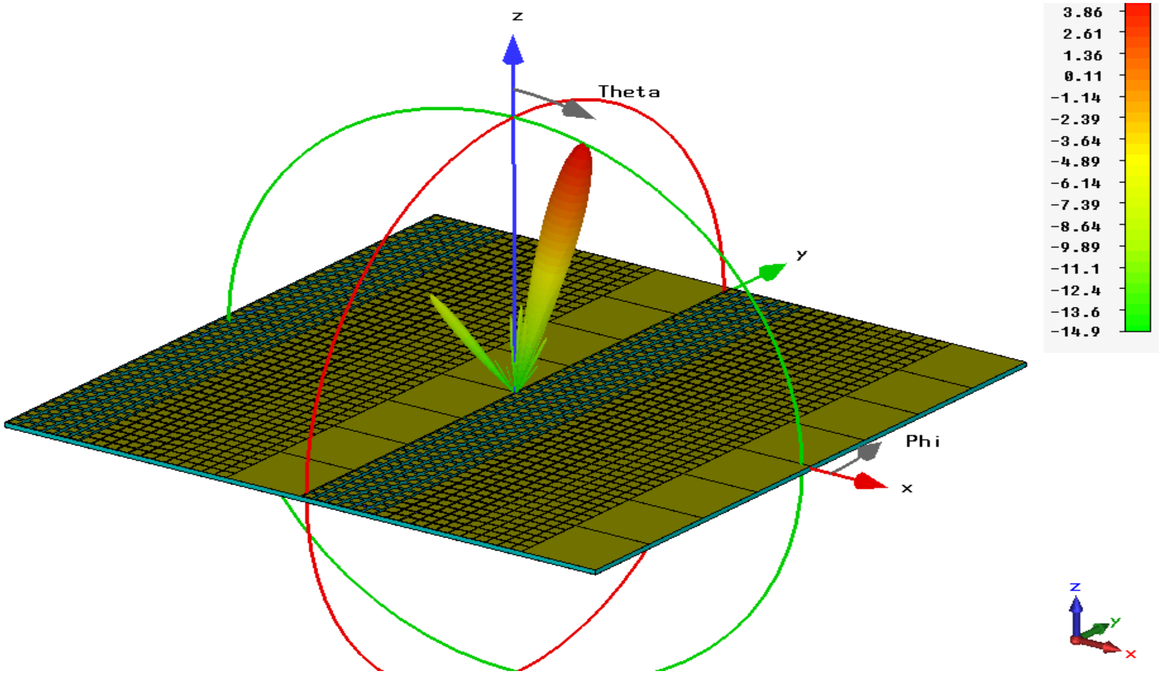
"00""01""10""11"

Sequence:

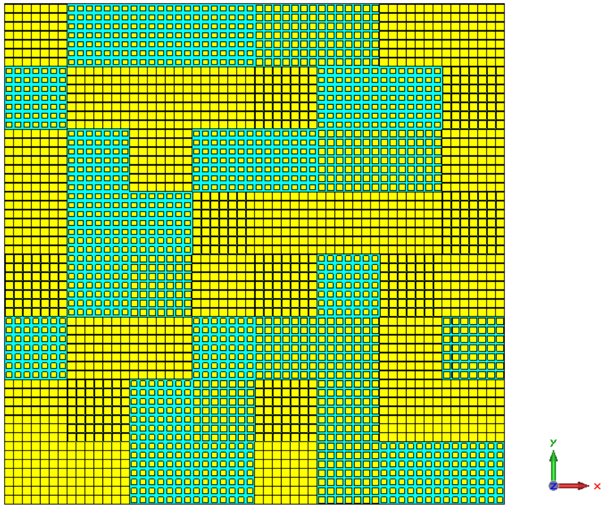
Gradient Phase

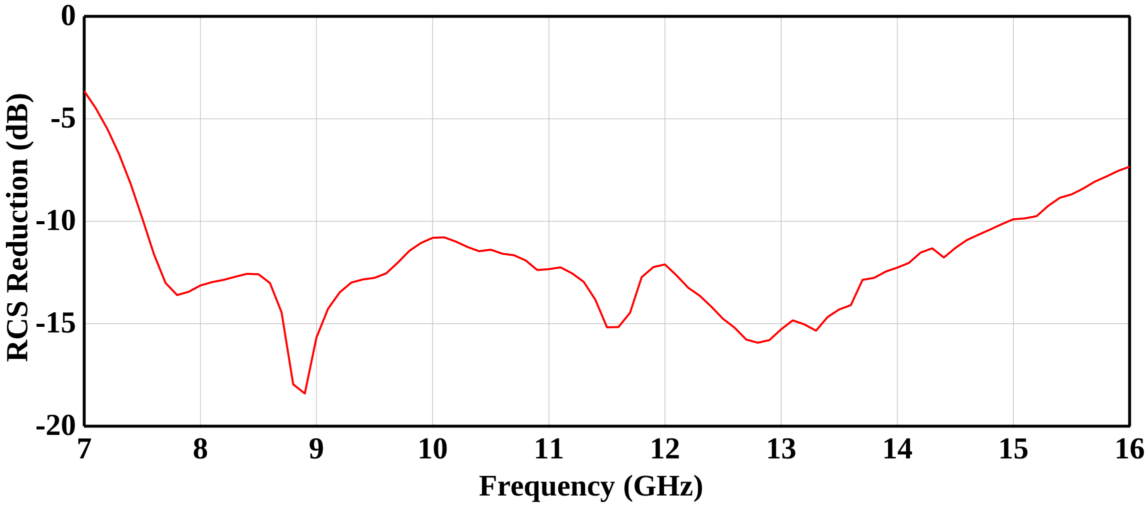

V/m (log)
2
1.44
1.04
0.741
0.524
0.365
0.249
0.164
0.102
0.0572
0.0242
0

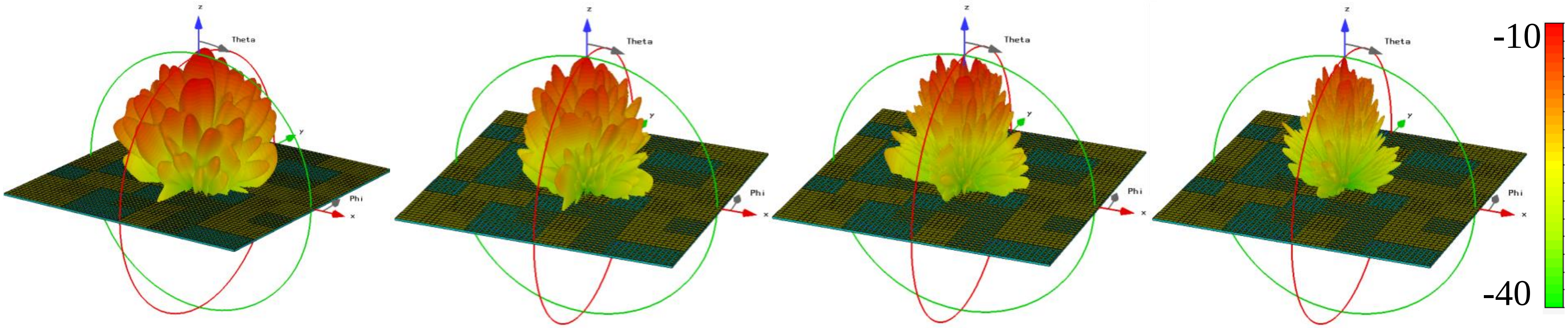
Generalized Snell's Law


z
Theta
y
Phi
x
3.86
2.61
1.36
0.11
-1.14
-2.39
-3.64
-4.89
-6.14
-7.39
-8.64
-9.89
-11.1
-12.4
-13.6
-14.9
z
y
x

2-Bit Coding Metamaterials






z
Theta
y
Phi
x
-10
-40

Better performance is observed for RCS reduction using 2-bit coding metamaterial

Digital Metamaterials

- ◆ **Coding metamaterials are not our final purpose**
- ◆ **We aim to realize digital control of coding sequence**

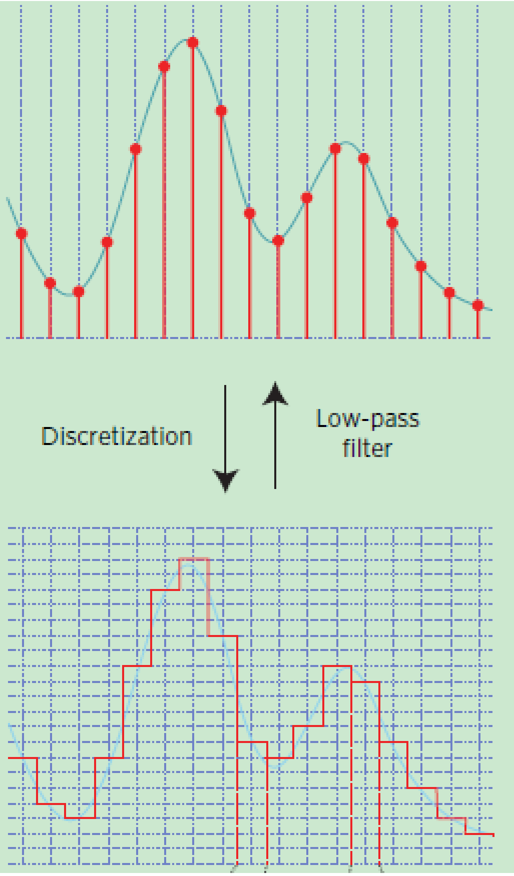
nature materials

ARTICLES

ONLINE: 14 SEPTEMBER 2014 | DOI: 10.1038/NMAT4082

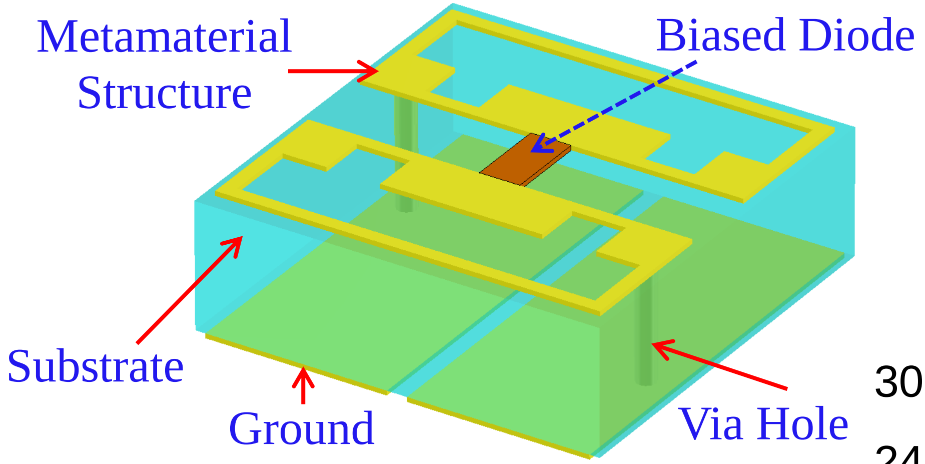
Digital metamaterials

Cristian Della Giovampaola and Nader Engheta*



- ◆ **This is a purely theoretical work.**
- ◆ **The “digital” here in fact means “discrete”.**
- ◆ **Our concept is proposed independently, and has totally different meaning: digitally control**

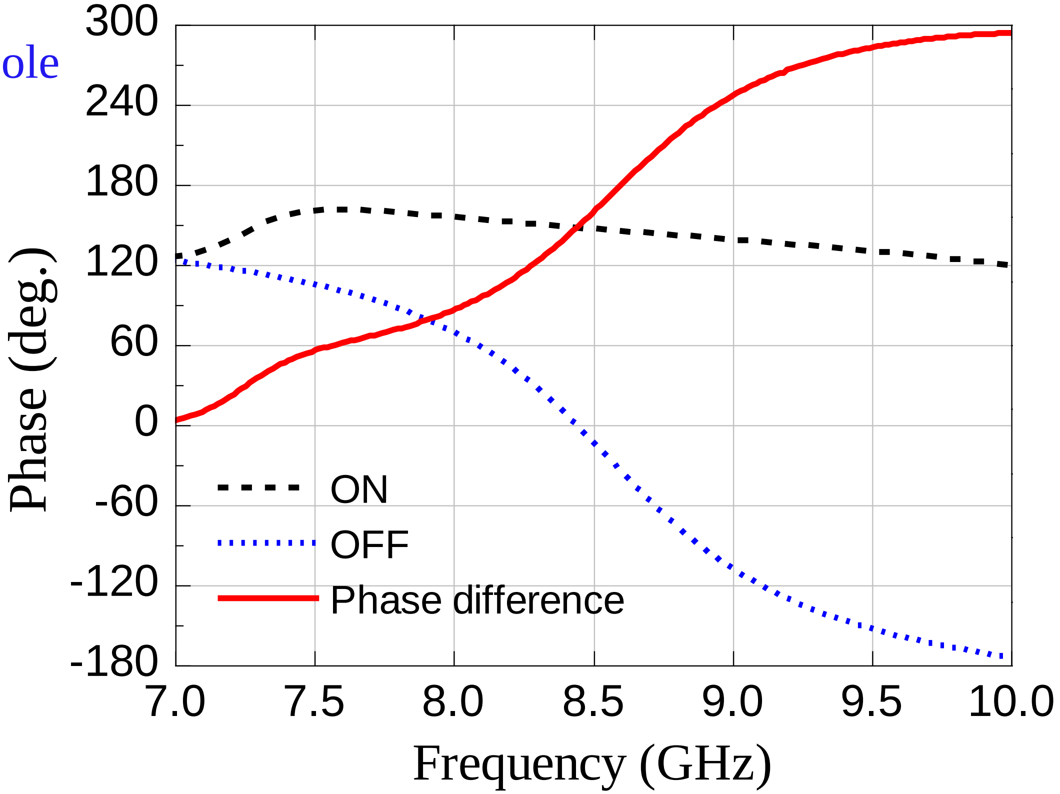
Digital Metamaterials


Metamaterial Structure
Biased Diode
Substrate
Ground
Via Hole

A unique metamaterial particle, which can be either 0 or 1, controlled by the pin diode.

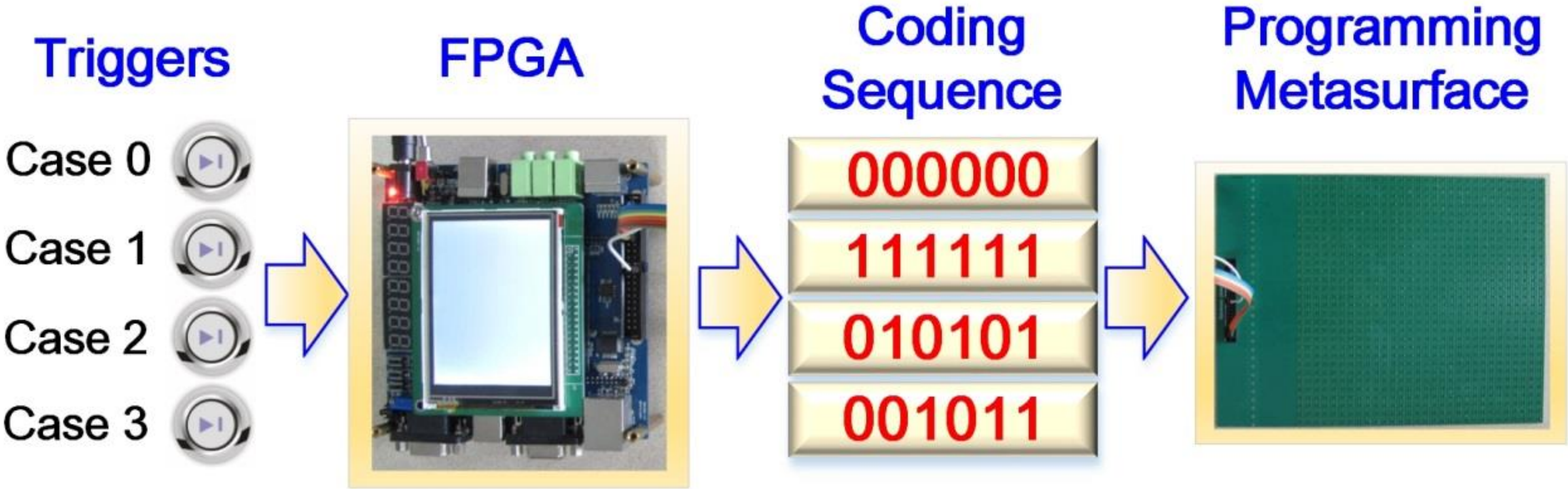
- ◆ **We can control the state of each particle as 0 or 1 by giving two different biased voltages.**
- ◆ **We can then control the coding sequences of 0 and 1**

The Phase Responses

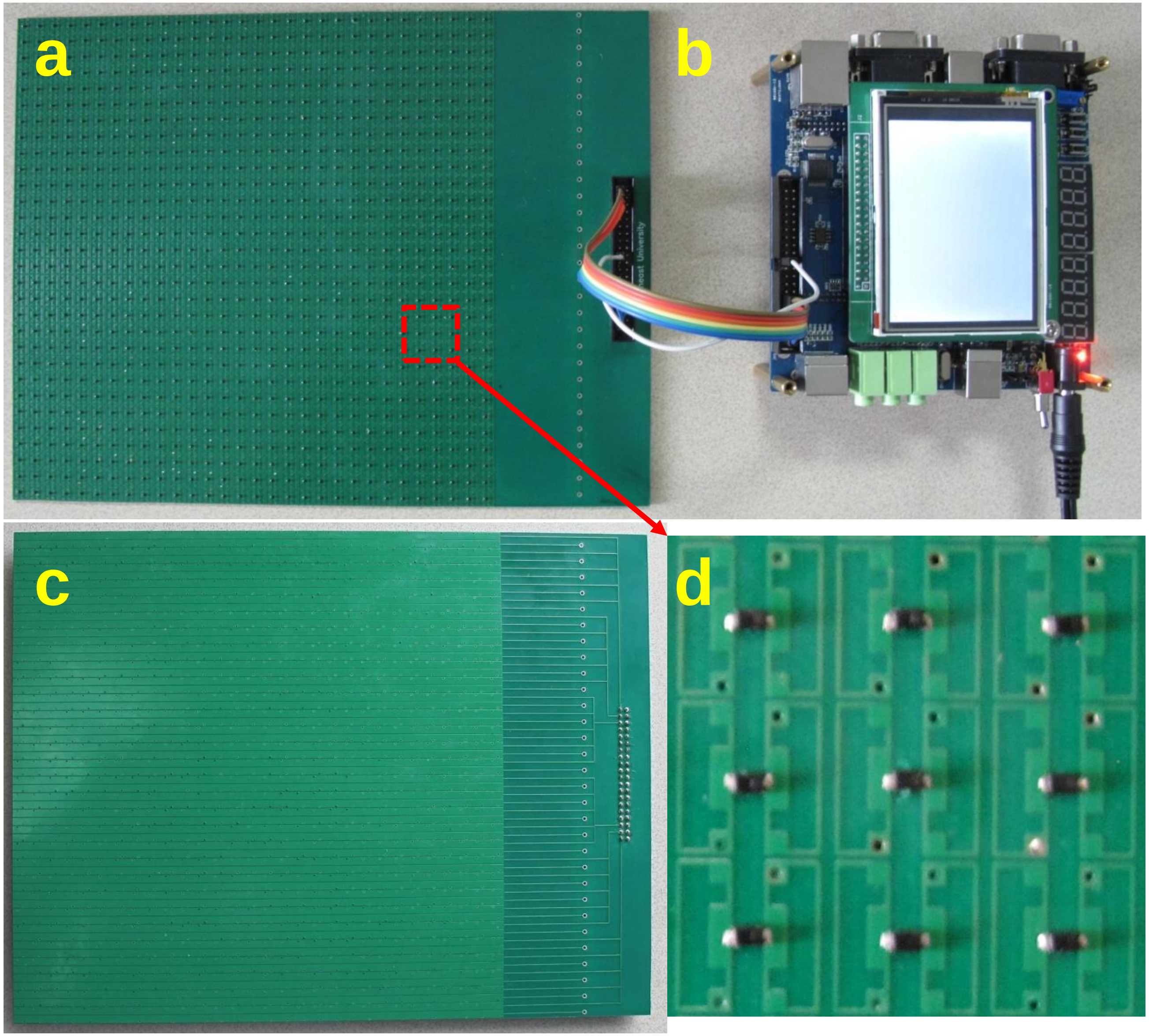


Programmable Metamaterials

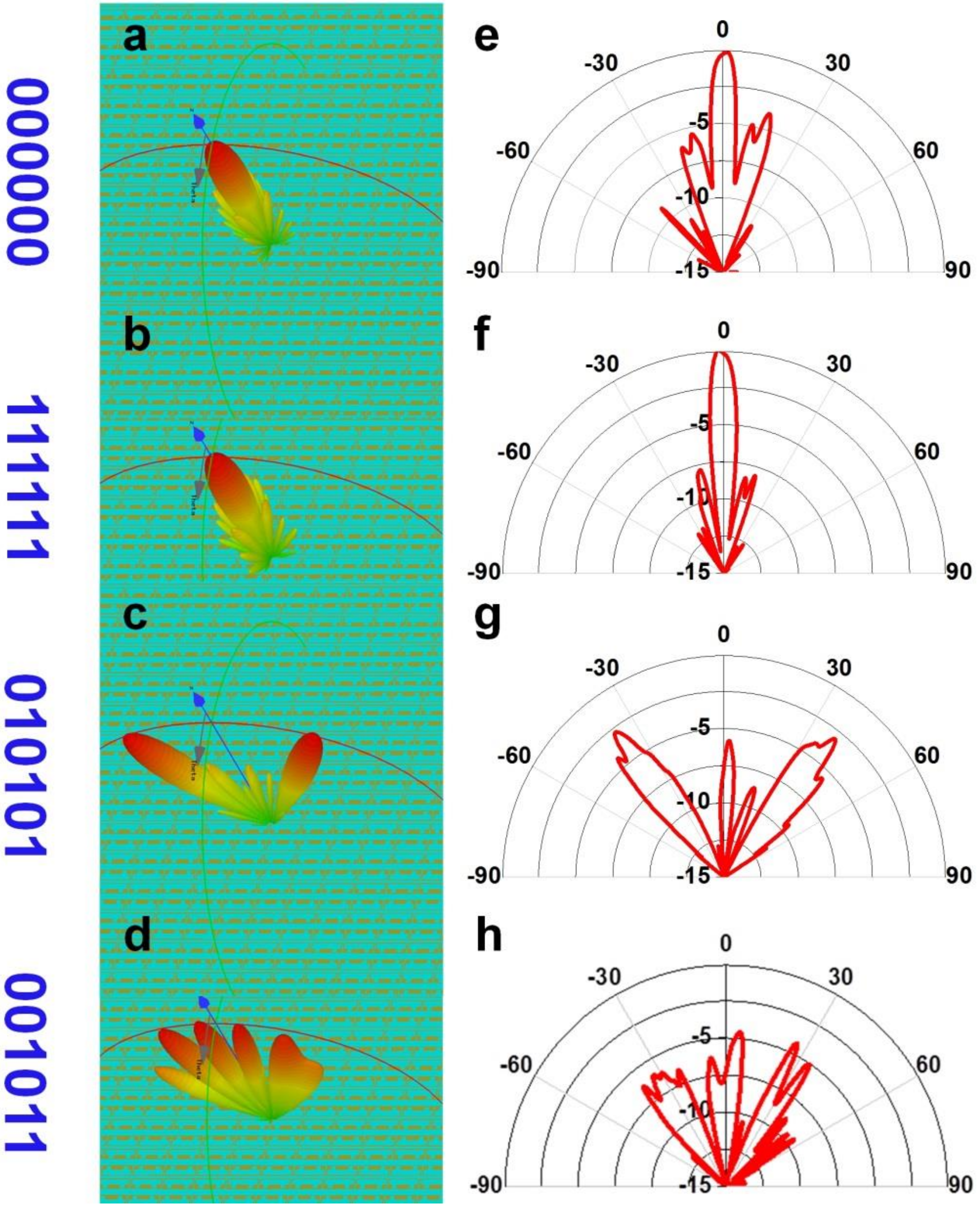
- **By using field-programmable gate array (FPGA) hardware, we realize digital control over the digital metamaterial.**
- **We can write a program consisting of many cases onto FPGA, which is used to control many functionalities in real-time: Programmable Metamaterial.**


Triggers
FPGA
Coding Sequence
Programming Metasurface
Case 0
Case 1
Case 2
Case 3
000000
111111
010101
001011

Programmable Metamaterials



Experimental Validation



- **A Simple Example:**
- **Six-Code Sequence**
- **Many functionalities can be realized by a single metamaterial, which are switched in real time, and computer controllable.**

Cui et al., Light: Science & Applications 3, e218; doi:10.1038/lsa.2014.99, 2014

Terahertz Coding Metasurfaces

L. H. Gao *et* al., “Broadband diffusions of terahertz waves by multi-bit coding metasurfaces,” submitted for publication, 2014

- **A novel coding particle: Minkowski fractal structure**
- **1-bit, 2-bit, and 3-bit coding particles can be realized using the Minkowski loops with different scales**

Summary

- Metamaterials can be characterized by two ways: - Effective medium parameters; - Spatial coding.
- We propose the concepts of coding metamaterial, digitally-controlled metamaterial, and programmable metamaterial.
- Coding metamaterials can be extended to higher orders, which have more freedom to control EM waves.
- We have realized 1-bit digital and programmable metamaterial using FPGA.
- We expect to realize 2-bit digital and programmable metamaterials in the near future.
- The coding metamaterials can be extended to THz waves

Thank you!

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